A semi-annual report for

STUDIES OF EXTRA-SOLAR OORT CLOUDS AND THE KUIPER DISK

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SwRI Project No.: 15-4971

Submitted by:

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This is the first semi-annual report for NAGW-3023 (SwRI Project 15-4971), *Studies of Extra-Solar Oort Clouds and the Kuiper Disk.*

We are conducting research designed to enhance our understanding of the evolution and detectability of comet clouds and disks. This area holds promise for also improving our understanding of outer solar system formation, the bombardment history of the planets, the transport of volatiles and organics from the outer solar system to the inner planets, and to the ultimate fate of comet clouds around the Sun and other stars. According to "standard" theory, both the Kuiper Disk and Oort Cloud are (at least in part) natural products of the planetary accumulation stage of solar system formation. One expects such assemblages to be a common attribute of other solar systems. Therefore, searches for comet disks and clouds orbiting other stars offers a new method for indirectly detecting the presence of planetary systems.

Our three-year effort consists of two major efforts: (1) modelling and observational work to predict and search for the signatures of Oort Clouds and comet disks around other stars and (2) modelling studies of the formation and evolution of the Kuiper Disk (KD) and similar assemblages that may reside around other stars, including β Pic. These efforts are referred to as Task 1 and 2, respectively. Task 2 is to be carried out as an integral part of Dr. Glen Stewart's proposed origins program.

Recent Results

Under Task 1, we undertook a first run at the JCMT to study one of the best IRAS IR-excess comet cloud candidates, α Psa (Fomalhaut), have begun the analysis of that data, and proposed for additional time to map the Fomalhaut system in more detail. The reduced data indicate there is evidence for dust around Fomalhaut at distances 10x greater (i.e., 2500 AU) than ever before detected, providing strong evidence for a population of distant comets or other bodies undergoing collisions. Observing proposals to extend this work to other stars, and to make a second-generation study of Fomalhaut have been submitted to JCMT and the ESO/IRAM submm observatories have during this quarter. The Time Allocation Committees (TACs) for these observatories have not yet met to evaluate proposals.

Under Task 2, we performed scaling calculations to determine the importance of (i) perturbations by passing stars and GMCs on objects in the Kuiper Disk and (ii) the role of protoplanetary gas drag in providing a lower size cutoff in the inital KD population, and (iii) the likelihood that large ($\sim 10^3$ km) objects populate the KD. We found that (i) although galactic tides remain to be evaluated, individual stellar and GMC perturbations are unlikely to be important for objects inside a few hundred AU; (ii) owing to drag during propotplanetary scattering events, objects smaller than $\sim$ 100 m should be strongly depleted in the initial OC/KD size distribution and (iii) numerous 1000-km bodies may have been present during the accretion of Uranus and Neptune and may now reside in the KD and OC. The later two results are directly related to the initial size spectrum of objects which must be included in our dynamical/collisional model. We have

also begun the development with Glen Stewart of the dynamical/collisional model needed to make progress on the KD studies. At present, 25% of the required model code is in place. The first publication resulting from the Stern/Stewart collaboration is now taking place. This work (Stern and Stewart 1992) reports the results of initial collisional calculations constraining the population structure of the Kuiper Disk, and making predictions concerning of the far-IR signature of the Kuiper Disk. We expect to submit this publication later this year. A popular paper (Stern 1992) has been published in *Astronomy* magazine describing the Stern (1991) paper which resulted from work on this project performed prior to funding.

References

Submm-Studies of Thermal Emission from a Large Dust Cloud Around the IR-Excess Star Fomalhaut. S.A. Stern and D.A. Weintraub, in preparation, 1992.

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Where has Pluto's Family Gone? (popular article). S.A. Stern, *Astronomy Magazine.*, September, 1992.

Collisions in the Kuiper Disk. S.A. Stern and D.A. Weintraub, in preparation, 1992.

Technical Presentations

Triton, Pluto, and Charon as Relics of a Large, Ancient Planetary Ice Dwarf Population. S.A. Stern, Spring AGU Talk, 1992.

Why Nine? On the Number of Planets in the Solar System. Astrophysics Seminar, University of California at San Diego and CalSpace, May, 1992.

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Date of registration :

PROPOSAL FOR 30 M TELESCOPE

Deadline : June. 1st 1992 - Period : Sept - December 1992

TITLE *(self-explanatory)*
Mapping the Extended, Cold Dust Cloud Around α PsA (Fomalhaut): A Comet Cloud or Disk?

Type : extragalactic : continuum ◯ CO lines ◯ other ◯
galactic : continuum ⊗ lines ◯ circumstel. env. ⊗ young stel. obj. ◯ cloud struct. ◯ chem. ◯ other ◯

ABSTRACT
In 1991 we detected extended, 1.1mm emission around Fomalhaut (α PsA) at distances in order of magnitude beyond previous detections. This emission is plausibly related to the presence of an extended comet cloud, like our Oort Cloud, and may therefore represent indirect evidence for the formation of a planetary system at Fomalhaut. We propose now to extend this work to create a map of the angular and spatial extent of this emission. Fomalhaut is the only known main-sequence, submm-resolved IR excess source beside β Pic.
max. 8 lines

Is this a resubmission of a previous proposal ? no ⊗ yes ◯ ; proposal number ....

Is this the continuation of (a) previous proposal(s) ? no ⊗ yes ◯ ; proposal number(s)................................

hours requested for this period : 24

LST range(s) : from : 19 H to : 03 H number of intervals :
from : to : number of intervals :

Number of hours foreseen for full completion for this proposal : 24 of which 0 were already allocated

Special requirements : *(dates, etc ...)* : NOTE: A minimum program would involve 16 hours.

Receivers : 3 mm Schottky ◯ ; 3 mm SIS ◯ ; 2 mm ◯ ; 1,3 mm SIS ◯ ; 345 SIS ◯ ; bolo ⊗

Frequencies *: (to 0.1 GHz and corrected for redshift) 240 GHz

List of Objects (give most common names) with equatorial coordinates

α PsA (Fomalhaut) $22^h\ 54.9^m$, $-29°\ 53'$

(continue on next page, if needed ; please send also by e-mail if list is long)

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Dr. Michel Festou, CNRS,
33-61-53-67-22

Expected observer(s) S.A. Stern, M.C. Festou

join to this form : scientific aims (≤ 2 typed pages + 1 page Figs., Tables) and list of related publications ** imperatively*

Mapping the Extended, Cold Dust Cloud Around α PsA (Fomalhaut): A Comet Cloud or Disk?

In 1991 we carried out an initial set of mm/submm observations of α PsA – the only known main-sequence, submm-resolved IR excess source beside β Pic. Those observations, made using the JCMT UKT14 facility bolometer, returned data at 1.1mm which indicate the presence of extended emission approximately as strong at distances of 2500 AU from α PsA as those 100 AU from the star (Stern & Weintraub 1992). Based on models of the sun's Oort Cloud and Kuiper Disk (*e.g.*, Weissman 1990; Stern, *et al.* 1991), one expects dust optical depth and submm emission to peak at $10^{2.5-3.5}$ AU from a star possessing a cloud of interacting (i.e., colliding) comets such as our own (Figure 1).

The main objective of this IRAM proposal is the *mapping* of cold dust around Fomalhaut (A3V; α PsA). Mapping is necessary to elucidate the structure of the Fomalhaut dust cloud, and thereby to address whether it is in fact related to an Oort-like comet cloud. The IRAM facility bolometer is the instrument of choice for this work because it is 3-4x more sensitive than the JCMT UKT14 (Thum, et al. 1992). As such IRAM observations can both (i) detect weaker emission and (ii) work faster at the moderately "strong" emission level (~25 mJy) already detected 2500 AU from Fomalhaut.

Detections of cold dust around main sequence stars were initiated by IRAS, first at Vega (Aumann, *et al.* 1984) and then around many other stars (Aumann 1985, Stencel & Backman 1991). Owing to the short dust lifetime against radiation pressure and Poynting-Robertson (PR) drag, the detection of continuum emission from dust around such stars strongly indicates a present-day dust source, which presumably consists of macroscopic objects (*e.g.*, comets or asteroids) undergoing collisions (*e.g.*, Weissman 1984). Thus, the detection of ***highly-extended*** IR and FIR emission naturally suggests the presence of an Oort Cloud or Kuiper Disk (Weissman 1984; Aumann 1985). Since comet clouds represent a 'smoking gun' of planetary formation (Stern, *et al.* 1991), comet cloud detection provides strong circumstantial evidence for the existence of an underlying planetary system.

Only a handful of the IRAS IR excess sources are close enough to permit spatial mapping of the excess emission region by submm/mm telescopes. Indeed, submm/mm searches for such extended emission have been reported around just 6 IRAS IR excess sources (*cf.*, Becklin & Zuckerman 1989; Chini *et al.* 1990). Positive detections of extended emission off the stellar line-of-sight (LOS) were made for only two of these: β Pic (16.6 pc distant) and α PsA (6.7 pc distant). Optical coronograph studies (Smith & Terrile 1984) and 0.8mm work by Becklin & Zuckerman (BZ) have revealed a disk-like assemblage reaching to $> 10^3$ AU around β Pic. Unfortunately, no well-studied analog to β Pic exists.

Previous to our 1991 work, Chini *et al.* (1990) detected 12x the 0.8mm emission along the LOS to Fomalhaut expected from a normal A3V photosphere, confirming the presence of cold circumstellar dust. BZ's 1989 study at 0.8mm revealed substantial continuum emission one JCMT beam-width ($\sim$ 100 AU) off the line of sight to the star in both the NW and NE directions (see Table 1). Based on this work and our own 1.1mm data, there is now good evidence for extended thermal emission from dust at several distances, and in at least two directions around α PsA.

We thus propose to make a much more complete exploration of the angular and spatial distribution of extended emission around Fomalhaut, using the IRAM 240 GHz (1.3 mm) bolometer. The osed study will (i) extend measurements of the dust emission to a distance 3x that already explored, and (ii) explore the shape of the dust distribution (*i.e.*, to determine whether the emission suggests a disk-like or spherical source). With these data, we plan to gather enough data to put the α PsA extended dust emission map on an equal footing with β Pic, so that detailed, comparative studies can begin.

In all, we wish to obtain 1.3mm measurements at 3-4 distances from Fomalhaut. At each distance, we will make measurements along the LOS to the star, and at orthogonal directions around α PsA (i.e., in a cruciform pattern). All previous work is limited to just four points distributed among two wavelengths (note Chini, et al only observed along the line of sight to the star). Three 8 hour shifts are requested to accomplish our objectives. Including calibration and normal observing overheads, we estimate we can make 3 to 4 ($4-5\sigma$ significance) integrations per shift (see Table 2). In addition to pushing to greater distances, this program will triple the number of mapping points so-far obtained.

Mapping will begin in the SE direction from α PsA (along the plane of strongest emission, opposite to the NW direction explored in 1991), stepping logarithmically outwards (*i.e.* ~2000, 4000, 8000 AU). Our goals are to determine (i) at what distance the emission peaks, and (ii) the the emission distribution both inside and outside the peak in order to shed light on the question of whether the extended dust is in a disk or shell. We note that BZ's NW and NE 0.8mm measurements 100 AU from α PsA indicate some preference for a tilted disk. The resolution of the disk *vs.* shell question directly relates to whether the dust is derived from a source in some inner, planetary plane or whether the source is instead related to spherical outflow more likely related to the A3V star itself.

The continuum emission detected at each station around α PsA will be used to model the optical depth distribution and total mass of orbiting dust. These parameters will be used to infer the mass and distribution of the underlying, macroscopic source bodies for the dust. Our model (*cf.* Stern, *et al.* 1991) employs a standard (*e.g.*, Mathis *et al.* 1977) size distribution, with optical coefficients for the dust taken from Draine (1985), assuming optically thin radiative transport. We will estimate the mass of the underlying bodies generating the dust taking into account production by collisions, as well as radiation, PR, and ISM drag losses (Stern 1990).

References

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Table 1
0.8 mm JCMT Observations of Main-Sequence IR Excess Stars

Star	Distance (parsec)	On Stellar Position (mJy/beam)	Flux At Offset 1 (mJy/beam)	Offset Position 1	Flux At Offset 2 (mJy/beam)	Offset Position 2
α PsA	6.7	35 ± 6.5	23.6 ± 12	14.2″E,8.2″N	40 ± 11	8.2″W,14.2″N
β Pic	16.4	80 ± 14	40 ± 26	7.4″W,15.″S	11.7 ± 17	7.4″E,15.″N
α Lyra	8.1	21.5 ± 5.4				

Table 2[a]
1.3mm Observing Time Estimates

Distance	IRAM NEFD	Predicted Flux (30-50 K)	3σ Limit (120 min)	3σ Limit (60 min)
1000 AU	90 mJy $Hz^{-1/2}$	5-15 mJy	1-2 mJy	2-3 mJy
2000 AU	90 mJy $Hz^{-1/2}$	9-28 mJy	1-2 mJy	2-3 mJy
4000 AU	90 mJy $Hz^{-1/2}$	3-10 mJy	1-2 mJy	2-3 mJy

[a] Assumes R-J spectrum from 1.1 to 1.3mm.

[b] The emission model used to make these predictions is for an Oort Cloud-like radial distribution (cf., Fig. 1); higher emission could be present if either (i) the 2500 AU points we surveyed in 1991 are not at the peak or (ii) if the interior region is not depleted, as in our solar system.

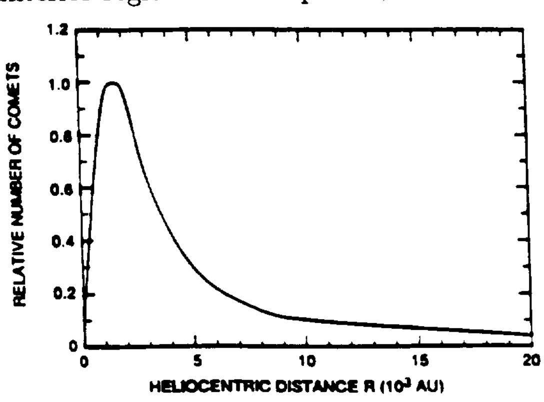

Figure 1: The expected radial distribution of comets in our Oort Cloud when projected onto the plane of the sky (from Stern, Stocke & Weissman 1991).

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APPLICATION FOR TELESCOPE TIME

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For Office use only REF:-

SEMESTER X (Feb. 1993 - Aug. 1993)

2 i) Principal applicant:
Surname Stern Title Dr. Initials Alan Possible observer ~~Y/N~~ Yes

Institution .... Department .... Post ....

ii) Principal observer (if different) same Y/N

iii) Collaborators (state institution)

D.A. Leahy/University of Calgary ~~Y/N~~ yes

D.A. Weintraub/Vanderbilt University ~~Y/N~~ yes

Y/N

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3 TITLE OF INVESTIGATION (12 WORDS MAXIMUM) Mini-survey for Cold Dust at Oort Cloud Distances Around IRAS IR Excess Stars

4 SCIENTIFIC CATEGORY ☐ Solar System ☒ Stellar ☐ Galactic & Interstellar ☐ Extragalactic & Cosmology ☐ Other

5. LONG TERM STATUS: ~~Y/N~~ No

If yes total number of useful nights/weeks needed to complete programme

HIGH FREQUENCY: ~~Y/N~~ No

6 ABSTRACT OF PROPOSED OBSERVATIONS

In late 1991 we used UKT14 to study extended, submm/mm emission at distances from Fomalhaut (α PsA) *an order of magnitude* beyond previous detections. That observing run appears to have resulted in the detection of cold dust at distances consistent with Oort Cloud detection. We propose now to extend such studies to a set of 6 other IRAS IR excess sources. The proposed observations attack the root objective of our NASA Origins of Solar Systems project to search for evidence for and then study the properties of extra-solar Oort Clouds around main sequence stars.

7 ABSTRACT OF BACK UP PROGRAMME FOR POOR OBSERVING CONDITIONS

We will undertake studies of CO 3-2 and ^{13}CO 3-2 emission from Herbig Ae/Be stars to search for molecular outflows, using RxB3 and the DAS.

8 DETAILS OF OBSERVING TIME, INSTRUMENTS ETC FOR THIS SEMESTER

NB. If own instrument, not previously used on telescope, attach a concise description on a separate page

Shifts (8 hours)	Frontend (see users manual)	Observing Frequencies (molecule/transition)	Sources
9	UKT14	0.8, 1.1mm	see attached Table 1

i) Preferred dates March-May

ii) Impossible dates (give reason) none

May 1989 revision

9 LIST OF PRINCIPAL SOURCES

Name	RA (hh mm)	Dec (dd)	Brightness/Flux (T_r*(K)/F(mJy))	Vlsr (km/s)	Linewidth (km/s)	Notes/priority

see attached Tables 1 and 2

10 BREAKDOWN OF TIME REQUESTED

a) Line observations Receiver(s) UKT14 Backend ....

Rest freq (GHz)	Req sensitivity (rms; K)	Freq resolution (MHz)	Total number of spatial points	Total time (hrs) (incl overheads)

b) Continuum observations Receiver UKT14

Filter (microns)	Aperture (arcsec)	Req sensitivity (mJy)	Total number of spatial points	Total time (hrs) (incl overheads)
800	13.5"(47mm)	8 mJy rms	5/star	24 hours(3 shifts total)
1100	19"(65mm)	4 mJy rms	5/star	48 hours(6 shifts total)

c) Other requirements (own instrument, polarisation, etc.)

11 OBSERVING

Sidereal time interval 07-22 hours (varies with target)

Observing support required ....

12 (i) Have applications for observing time time on other telescopes/satellites for this or similar programmes in the coming semester been made YES/NO

(ii) If YES state: a) Telescope/satellite ....

b) Title of programme ....

c) Whether simultaneous observations required YES/NO

(i) Related PATT applications over last 4 semesters (include unsuccessful applications)

Semester Year	Telescope	Ref	Request	Allocated	Clear nights	Comments
U/1991	JCMT	M/U/016	3	3	2	good data at 1.1mm
W/1992	JCMT	M/W/062	6	0	N/A	1st quartile, no time awarded

(ii) Title and reference of all publications (incl. preprints) over last 4 semesters which have resulted from PATT time

Initial detection of extended submillimeter emission around Fomalhaut, Stern, S.A., and D.A. Weintraub, Science, in preparation.

(iii) Other publications relevant to this application

14 (i) Are the observations primarily for a student research training programme? ~~YES/NO~~ NO

If YES, state a) Name of student(s) ....

b) Project title(s) ....

c) SERC studentship no(s) (UK only) ....

(ii) Are the observations associated with a current research grant? ~~YES/NO~~ YES

If YES, state a) Name of principal investigator S.A. Stern

b) Grant number NASA NAGW-2914

15 Indicate experience of intended observers who have not previously used this telescope

all three observers have JCMT experience

16 FUNDING

Funding Source

(i) Name | No. of nights | Reason (data reduction, etc.) | SERC/NRC/ASTRON/OTHER

(ii) Please indicate any other anticipated expenditure (freight, remote observations etc.)

(Case NOT to exceed this A4 page. One side of diagrams references may be attached if desired)

Detections of cold dust at significant distances around main sequence stars was initiated by IRAS, first at Vega (Aumann *et al.* 1984) and then around many other stars (Aumann 1985; Stencel & Backman 1991). Owing to the short dust lifetime against radiation pressure and Poynting-Robertson (PR) drag, the detection of continuum emission from dust around such stars strongly indicates a present-day dust source, which presumably consists of macroscopic objects (*e.g.*, comets or asteroids) undergoing collisions (Weissman 1984). Therefore, the detection of *highly-extended* IR and FIR emission naturally suggests the presence of an Oort Cloud or Kuiper Disk (Weissman 1984; Aumann 1985).

Submm/mm searches for (and in several cases detections of) extended emission from dust have been reported around only a few IRAS IR excess sources (*cf.*, Becklin & Zuckerman 1992 (BZ); Chini *et al.* 1990). In all cases except our Fomalhaut work and BZ's β Pic work, submm/mm searches have been limited to distances of 100-200 AU or less from the parent star. (Of course, optical coronograph studies by Smith & Terrile (1984) have revealed a disk-like assemblage reaching to $> 10^3$ AU around β Pic).

The critical distinction we emphasize is that while dust at distances of 100-200 AU is interesting and may well be related to comet disks and even planetesimal formation, dust at > 1500 AU represents a 'smoking gun' for giant planet formation (Stern, *et al.* 1991). The reason for this is that, assuming the dust is generated by comet collisions (the standard model), giant planets are required to scatter comets to such large distances (this is how our Oort Cloud was formed). As such, comet cloud detection provides extremely strong evidence for the existence of an underlying planetary system with giant planets acting as scattering centers.

Our NASA Origins research program is focused on determining the frequency and physical properties of Extra-Solar Oort Clouds (ESOCs). Last year we carried out an initial set of JCMT observations of α PsA, the only known main-sequence, submm-resolved IR excess source beside β Pic. We were able to obtain data at 1.1mm which indicate the presence of extended emission at distances of 2500 AU from α PsA (Stern & Weintraub 1992). This is just where models of the sun's Oort Cloud and Kuiper Disk (*e.g.*, Weissman 1990; Stern, *et al.* 1991) predict dust optical depth and submm emission to peak (i.e, 500-3000 AU from the star itself; cf., Figure 1). This is much also further out than past dust detections around main sequence stars, and strongly indicates Fomalhaut has an extended comet cloud undergoing mutual collisions (cf., Stern 1988). Emission at even larger distances may be detectable; we did not have time to complete such a search.

This proposal for Semester X requests time to conduct a search for cold dust assemblages around other stars which IRAS and/or JCMT/IRAM observations have shown are sources of excess IR and submm/mm emission, and are therefore good ESOC candidates. The objective is to determine if β Pic and Fomalhaut are-anomalous or just the 'tip of an iceberg,' representing a broadly common phenomenon related to planetary formation. Table 1 gives the list of 6 candidate stars for our program. We note that these 6 stars branch out beyond AV dwarfs like Fomalhaut and Vega to determine whether such assemblages may be common to other IRAS IR excess types as well. Depending on the number and dates of shifts awarded, we will select a subset of 3-5 of these stars for observation.

As in our Semester U/Fomalhaut program, we will use UKT14 to make our search. The search strategy will be to make observations at 1.1mm in a five-point cruciform around each program star at a distance of 2500 AU. By observing 4 points uniformly distributed in azimuth about the parent star, we can make effective use of JCMT's AZ/EL chopping system. The result of such an observing strategy gives us both a measure of the extent of emission at 2500 AU, as well as a constraint on the geometry of the source at 2500 AU.

Objects orbiting 2500 AU from their parent stars are subject to considerable perturbations from both passing stars and GMCs (cf., Weissman 1990). One expects dust around mature main sequence systems to reflect the distribution of underlying parent bodies (e.g., comets), and therefore to be widely distributed in plane-of-sky azimuth around the star (i.e., a dynamically hot dust distribution). The five-point cruciform search will allow us to address the question of whether detected emission is derived from either a thick- or tilted- disk, or instead from a more spherical shell.

For a canonical distance of 10 pc and a UKT14 beamwidth of 19 arcsec at 1.1mm, 2500 AU corresponds to 13 beamwidths from the parent star. All of our program stars are between 3 and 16 pc, thereby putting the 2500 AU point 7-43 beamwidths off the star. Confirming observations at 1.3 or 0.8mm will be made around those stars for which we find evidence for 1.1mm excess at 2500 AU.

Including offset-pointing, calibration, and normal observing overheads, we estimate UKT14 can complete 1 five-point cruciform search (i.e., one target) per shift at 1.1mm, with a detection limit of 15-25 mJy (4σ). Each cruciform point will consist of 4-8 1000 sec integration blocks interspersed with calibrator and/or pointing updates, as required. In total we request 1 shift for each of the 6 program stars, and 3 shifts for confirming 0.8mm observations on detected sources. As a reduced request, we ask for a minimum of 4 shifts to study 2-4 stars (depending on the number of 1.1mm detections made). Observations at Fomalhaut will be made at 1.1mm at 4000 AU and 0.8mm at 2500 AU to extend on the UKT14 work done in semester U.

The continuum emission detected at each cruciform station and along the LOS to the star will be used to model the optical depth distribution and total mass of orbiting dust around each program star. This emission will be modeled with a submm/mm dust radiative transfer code developed for just such studies at the University of Calgary (cf., Marshall, Leahy, & Kwok 1992). The model results will be used to infer the mass distribution of the underlying, macroscopic source bodies for the dust. The model employs a standard (*e.g.*, Mathis *et al.* 1977) size distribution, with optical coefficients for the dust taken from Draine (1985), assuming optically thin radiative transport. We will estimate the mass of the underlying bodies generating the dust taking into account production by collisions, as well as radiation, PR, and ISM drag losses (Stern 1990).

This mini-survey of potential Oort Cloud sites is a natural precursor to determine the appropriate strategic and stellar selection criteria for more extensive work using SCUBA in future years.

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Table 1
ESOC Search Program Stars (Ordered by RA)

Target	Coords/IRAS Name	Distance (pc)	Type
Procyon	07366+0520	3.5	F5IV wd
DM-23'8646	09399-2341	12	F9IV
β Leo	11464+1451	12	A3V
η CrB	15211+3027	16	G3V G0V
α Lyr (Vega)	18352+3844	7.5	A0V
α PsA (Fomulhaut)	22549-2953	6.7	A3V

Table 2[a]
UKT14 ESOC Observing Time Estimates

λ	JMCT NEFD	Predicted ESOC Flux (30-50 K)	3σ Limit (120 min)	3σ Limit (60 min)
0.8mm	0.7 Jy $Hz^{-1/2}$	24-75 mJy	24 mJy	35 mJy
1.1mm	0.3 Jy $Hz^{-1/2}$	13-40 mJy	11 mJy	15 mJy
1.3mm	0.3 Jy $Hz^{-1/2}$	09-28 mJy	11 mJy	15 mJy

[a] Assumes R-J spectrum extrapolated from 0.8 mm observations. Predicted ESOC fluxes are based on the Fomalhaut (α PsA) model.

Figure 1: The expected radial distribution of comets in our Oort Cloud when projected onto the plane of the sky (from Stern, Stocke & Weissman 1991).

We have read the Notes for Guidance relating to applications to the Panel for the Allocation of Telescope Time and if an award is made, understand that all participants may be required to sign a form of indemnity before being permitted to use the equipment. We are not bound by any contrary conditions governing the proposed investigation including obligations to third parties incurred in respect of ownership and use of research results and patents

	Signature	Date
Principal Applicant	[signature]	9/ /92
Principal Observer	[signature]	9/17/92
Head of Applicant's Department/Establishment	Nick Eaker	9-17-1992
Administrative Authority (State position held)	N/A	

SUBMISSION OF APPLICATIONS

The original typed copy of the completed application form and scientific case for support, together with EIGHT copies of each and at least THREE copies of any supplementary material, should be despatched to reach the council by the appropriate closing date (see below) and should be addressed to:-

The Executive Secretary,
Panel for the Allocation of Telescope Time,
Science and Engineering Research Council,
Polaris House, North Star Avenue,
SWINDON SN2 1ET U.K.

CLOSING DATES

SEMESTER:		Applications must be received on or before:
	August-January	31 March
	February-July	30 September

TO BE COMPLETED BY THE APPLICANT

INVESTIGATOR(S) DEPT(S)/ INSTITUTION(S)/T&S REQUIREMENT	SHORT TITLE OF INVESTIGATIONS	COMMENTS AND SCHEDULING PREF.	NO. OF SHIFTS (8 HOURS) REQUESTED	MINIMUM
S.A. Stern Space Sciences Dept. Southwest Research Institute	Oort-Cloud Mini-Survey	2 shifts/day March-May preferred could be 2 separate runs (e.g. 4 shifts, 5 shifts)	9	3-4

ADDRESS FOR ACKNOWLEDGEMENT

Dr. Alan Stern/Div 15
Space Sciences Dept.
Southwest Research Institute
6220 Culebra Rd.
San Antonio, TX 78238

SCIENCE AND ENGINEERING RESEARCH COUNCIL
POLARIS HOUSE,
NORTH STAR AVENUE,
SWINDON SN2 1ET

We acknowledge receipt of your application form dated please quote reference / / in future correspondence.

ASTRONOMY MAGAZINE, SEP 92 (...)

Where has Pluto's family gone?

Hundreds of icy Pluto-like planets may have roamed the outer solar system before being ejected into the vast comet cloud.

by Alan Stern

Textbooks tell us two main groups of planets make up the solar system. One group consists of four dense, rocky, terrestrial planets that circle in tight orbits tucked within a distance less than twice Earth's distance from the Sun. The other consists of four gargantuan, low-density gas giants that orbit between 5 and 30 times Earth's distance from the Sun. Just beyond the last of the gas giants lies icy Pluto. This tiny world traces an unusually inclined and eccentric orbit and, at 0.2 percent of Earth's mass, it is significantly smaller than any of the other eight planets.

Pluto's size and orbit are unlike those of any other planet, suggesting that it is a misfit. While the origin of the other planets is relatively clear, it is difficult to explain how this single little world developed at the ragged edge of the planetary system. Pluto appears to be a loose end that challenges our conventional view of the solar system's architecture.

One theory explaining the formation of Pluto suggests that the planet is an escaped satellite of one of the giant planets. Another suggests Pluto could have formed as the by product of a collision that occurred during the construction of Jupiter, Saturn, Uranus, and Neptune from smaller icy bodies. Or is it something else?

Formation of the Planets

Over the last several decades astronomers have established a standard model for the origin of the planets. This model states that the solar system started when an interstellar gas cloud collapsed gravitationally. The continued collapse of the cloud heated the central portion of the gas until nuclear fires were kindled, creating the Sun.

The spinning of this gas cloud caused dust and gas left over from the formation of the Sun to form a disk. In-falling interstellar dust grains — and dust grains that formed in the nebula itself — suffered a frictional drag from gas particles in the nebula that caused them to settle down to a narrow plane. This plane lay at the center of the disk formed by gas particles and was perhaps tens of thousands of times thinner.

The dust grains were composed primarily of silicon- and carbon-based materials, and water, methane, and carbon monoxide ices. Where the density of grains was high enough, collisions frequently took place between particles in nearby orbits. These gentle collisions caused the grains to grow. Gravitational instabilities in the dust disk accelerated this growth, which caused groups of growing grains to condense and form kilometer-sized "planetesimals."

From the study of very young solar-type stars, called T Tauri stars, it's clear that the formation of dust and gas disks around stars is common. But the T Tauris also have strong stellar winds that quickly dissipate their dust and gas disks. Observations of hundreds of T Tauri stars in the Orion and Taurus-Auriga stellar nurseries indicate that every

ORIGINAL PAGE OF POOR QUALITY

solarlike T Tauri star blows its disk away after 1 to 10 million years of nuclear burning.

The tiny dust grains and pebbles in the disk are highly susceptible to drag from these winds. Unless the small particles can assemble into larger, less drag-susceptible objects, they will be blown out of orbit around the star and back into interstellar space. Fortunately, computer simulations of planetesimal growth in the solar nebula indicate that drag-resistant, kilometer-sized planetesimals can form before the onset of the T Tauri wind.

Like the tiny dust grains they grew out of, planetesimals collide while in orbit around their star. Oftentimes, the collisions are gentle enough that the planetesimals grow in size. This process, known as planetesimal accretion, builds up larger and larger bodies until a few of the fastest-growing planetesimals exceed a critical mass, at which point their gravitational attraction becomes a significant aid to growth.

Then these bodies can attract other planetesimals in neighboring orbits that would not otherwise collide. Because each collision resulting in accretion adds more mass to these bodies, the process accelerates rapidly, creating runaway growth. In this runaway process, the first objects to reach critical mass grow faster and faster until all the material in the nebula eventually accretes into planets or is gravitationally ejected to distant orbits by near misses with the growing giant planets.

Astronomers believe such ejections populated the distant Oort cloud with 100 billion icy planetesimals, more commonly called comets. Once accretion and ejection exhaust the supply of planetesimals, the accretion phase of planetary formation is complete.

Some evidence for this accretion process comes from chemical studies of the Moon that indicate the Moon was formed most likely as the result of a collision between a Mars-sized body and young Earth. Other testimony for the accretion process comes from the differing compositions of the asteroids and planets, the atmospheric composition of the terrestrial planets, and the ubiquitous cratering seen on the Moon, Mercury, and the satellites of the giant planets. Craters ranging in diameter from tens to hundreds of kilometers scar the airless planets and satellites. Many of these craters were formed by the final clearing of planetesimals as the accretion phase drew to a close.

An Unlikely Bump in the Dark

Given this general view of planetary formation, it's not too difficult to imagine Pluto simply as a lone relic embryo of planetary formation that was fortuitously ejected to a not too distant yet safe orbit, where it has remained ever since. Indeed, Pluto's orbit remains protected because the orbits of Pluto and Neptune are gravitationally locked in a state called resonance that prevents Pluto from approaching closer to Neptune than 17 astronomical units. (One astronomical unit, or AU, is the average distance between the Sun and Earth.)

So why the fuss? Why is Pluto's existence so hard to reconcile with

ASTRONOMY: Lee Vande Visse

the architecture of the solar system? The problem is Charon, Pluto's only moon, which was discovered in 1978 by James Christy of the U.S. Naval Observatory.

A series of mutual eclipses of the planet and its satellite from 1985 to 1990 revealed that Pluto and Charon are a highly unusual pair. Both Pluto and Charon have low densities and icy surfaces, which indicates that they formed in the cool, outer part of the solar system. While most planets are much larger than their satellites (see the illustration above), Charon is half the size of Pluto and about 20 percent of Pluto's mass. Even the Earth-Moon system, sometimes called a double planet, is nowhere near as similar in size and mass, with the Moon being about one-quarter the size of Earth and having only about 1 percent of Earth's mass.

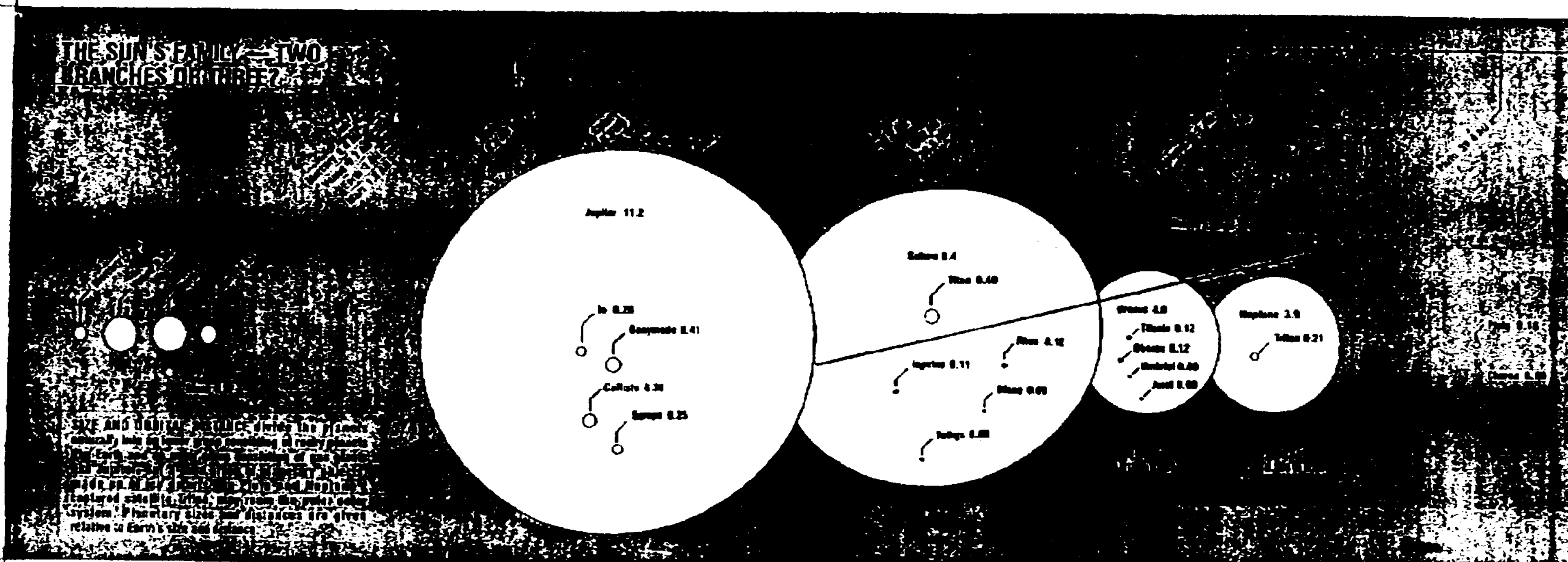
No known process could cause Pluto to form such a comparatively large satellite during accretion. Further, the angular momentum of the Pluto-Charon pair rules out the formation of Charon by the splitting of a rapidly rotating proto-Pluto into one large and one small piece.

Instead it appears Pluto and Charon formed independently and then collided, forming the present Pluto-Charon pair. This scenario, first suggested in 1984 by Bill McKinnon of Washington University in St. Louis, is supported by evidence that the other hypotheses cannot easily explain. This includes the similar masses of Pluto and Charon, the 17° tilt of Pluto's orbit, the large eccentricity of Pluto's orbit, and the fact that both Pluto and Charon rotate on their sides as Uranus does, with their rotation axes lying in the plane of their orbit. Pluto's orbital eccentricity may be related to the force of the collision between Pluto and Charon. Most planetary scientists now favor this model.

Despite its present popularity, the collision theory does face one difficult hurdle. It is highly unlikely that two small planets would experience such a collision in the vastness of the outer solar system. Some of my recent research points out the very low probability of such a collision. Using numerical calculations, I demonstrated that if Pluto and Charon started in separate orbits in the outer solar system, they would not, in all likelihood, collide, even over the age of the solar system.

To compute the collision probability of Pluto and Charon, we use the same principles used by 19th-century physicists to model the motions of molecules in a gas. This "particle-in-a-box" approach estimates the probability that two or more particles in a container of known volume will collide with one another within a specified period of time. For the Pluto-Charon collision, this standard approach requires knowing only three things: their sizes, the volume of space in which Pluto and Charon orbit, and the relative velocities of the pre-collision orbits.

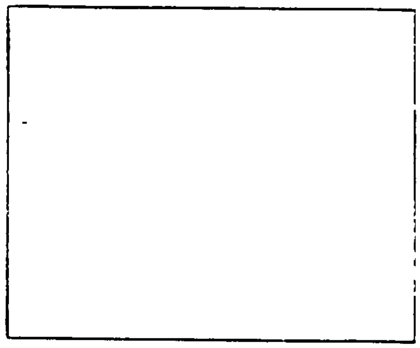
Over a range of reasonable values for these variables, the probability of Pluto's physically running into Charon is negligible — less than one in a million over the age of the solar system. Another way of saying this is that Pluto and Charon, orbiting alone in the outer solar system, would not


THE SUN'S FAMILY — TWO BRANCHES OR THREE?
Jupiter 11.2
Ganymede 0.41
Saturn 9.4
Titan 0.40
Uranus 4.0
Neptune 3.9
Triton 0.21

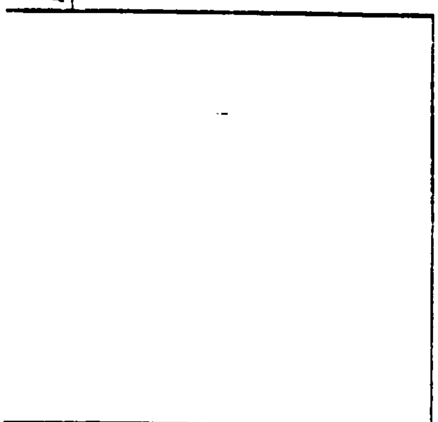
Ice Dwarfs: minor planets or major rocks?

All photos pages 44-47 by NASA

Amalthea



Hyperion



Proteus

The small sizes of the ice dwarfs raise the question as to whether these bodies are true planets or not. Obtaining an answer is not easy because no official definition of what constitutes a planet exists. But we can construct a good working definition.

To classify a body as a planet, it is reasonable to ask that it satisfy three criteria. First, the object must directly orbit the Sun rather than some other body, as a satellite does.

Next, the body must be massive

have collided in 4.5 billion years unless the most extraordinary of coincidences took place.

An attractive solution to Pluto and Charon's unlikely collision is to increase the number of small, Pluto-like planets swarming about the outer solar system during the era when Uranus and Neptune formed.

With many more bodies orbiting in the same region, the collision probabilities increase rapidly as the square of the number of bodies. The one in a million chance stated above increases to about one in a hundred for 100 bodies. To make the collision between Pluto and Charon likely (a 50/50 chance) requires roughly 1,000 Pluto-like bodies residing in the 20 to 30 AU region, even if we assume the collision took place anytime during the 4.5-billion-year history of the solar system. (But collisions are still rare because the average distance between these bodies is roughly 1 AU.) Depending upon uncertainties in the original orbital distribution of these bodies and the time scale during which they were present in the Uranus-to-Neptune zone, the actual population of small, icy planets implied by the presence of the Pluto-Charon binary could have been as small as a few hundred or as large as ten thousand. Although this range of uncertainty is large, the point remains that many more bodies than the ones we see today were required to make the Pluto-Charon collision likely at all.

It's certainly a radical departure from the standard view of solar system architecture to expect that in addition to the nine known planets, hundreds or thousands of icy planets 1,000 to 3,000 km in diameter also formed. But the case for a population of small icy planets, or "ice dwarfs," is not at odds with other important constraints on the formation of the outer solar system.

One such constraint is the total amount of material available in the region where Neptune and Uranus formed. Recent simulations of planetary formation in the outer solar system indicate that the formation process was not efficient. As much as 100 Earth masses of material probably resided in the Uranus-to-Neptune zone when accretion began, but only about 30 Earth masses of material altogether went into Uranus and Neptune. Because Pluto-like ice dwarfs are small and not very dense, even 1,000 of them would add up to only 2 Earth masses of material. Since these formation models indicate that 30 to 70 Earth masses of excess material were ejected from the region, it is not unreasonable to expect that ice dwarfs made up a few percent of the ejected objects.

More Roads to Rome

Based only on the low probability of a collision forming the Pluto-Charon pair, the case for hundreds or thousands of small icy planets is intriguing, but hardly compelling. What makes the ice dwarf hypothesis more convincing are the other lines of evidence pointing to the same conclusion.

The first of these concerns Triton, Neptune's largest satellite. Triton is only slightly larger than Pluto. It orbits Neptune in a retrograde — clockwise, as seen from north of the planet, rather than counterclock-

Miranda

Enceladus

enough to become round owing to the force of its own gravity. This condition requires that the object's mass rather than its composition control the body's shape. Roundness due to mass is the hallmark of a planet. A quick check of Voyager images of small satellites shows that very small (10 to 100 kilometers in diameter) satellites have a variety of irregular shapes, making them little more than orbiting rocks. Similarly, Voyager images of icy satellites also show that bodies become increasingly round as self-gravity begins to play a role. Calculations based upon mass and material properties show that the transition from an irregularly shaped to a gravitationally rounded body takes place for objects 200 to 400 km in diameter. The exact size depends upon the object's composition and how fast it rotates. Voyager images of satellites throughout the outer solar system support these calculations.

The final criterion for planethood is that a body cannot be so large that it can ignite nuclear fires in its interior and thus become a star.

This three-point test for planets isn't perfect, but it does serve as a guide as to which bodies may be planets. It limits the high and low ends of the size or mass for planetary bodies. By these criteria, meteors and most asteroids fail to qualify as planets. But the largest asteroids do qualify as planets, as do the ice dwarfs of 1,000- to 3,000-km diameter (Charon, Pluto, Triton, and their suspected brethren).

wise as for most satellites — orbit, which is recognized as the signature of a capture from a solar orbit.

Planetary scientists, including McKinnon and Caltech's Peter Goldreich, have studied different methods by which Neptune could have captured Triton. Possible capture scenarios include direct orbital capture, capture assisted by gas drag in Neptune's atmosphere or the proto-Neptune nebula, and capture following a collision between a sun-orbiting Triton and a primordial satellite of Neptune. In each case, computer simulations show capture to be extremely improbable. Neptune's capture of a Triton orbiting the Sun only becomes probable if several hundred "Tritons" orbit the Sun near 30 AU.

Even more evidence for the formation and former presence of a plethora of icy primordial planets in distant heliocentric orbits is provided by the tilts of Uranus and Neptune. Uranus' rotation axis is tilted 98° to its orbital plane, so its poles lie almost along its orbit. Neptune's rotation axis is tilted almost 30°. Alastair Cameron and his co-workers at the Harvard-Smithsonian Center for Astrophysics have found that large tilts imply collisions with other planet-sized bodies toward the end of the planet's accretion phase. To produce such large tilts, the impactors need masses between 0.2 and 5 Earth masses, depending upon the impact speed and the direction of the blow. Studies of the collision probabilities estimate that about 50 such planetary bodies would be required to make such collisions likely. Although these bodies are much larger than the ice dwarfs predicted by the Pluto-Charon collision and Triton's capture, they do indicate that many objects larger than the tiny, cometlike planetesimals formed in the early outer solar system.

In such a scenario, Pluto, Charon, and Triton are simply the relics of a once-larger population of small planets. Pluto, Charon, and Triton are still in the 20 to 30 AU zone because they are in protected dynamical niches, free from the possibility of accretion or ejection. Pluto and Charon are protected because of the resonance with Neptune, which keeps the pair from approaching close to Neptune. Triton has been protected from accretion or ejection because it is in orbit about Neptune.

It's interesting to note, however, that Triton's retrograde orbit is predicted to decay in several billion years, at which time it will crash into Neptune and merge with it. If we were living after that event rather than now, the clue that Triton provides wouldn't be known to us.

Taking each clue in isolation, we can reasonably conclude that the formation of the Pluto-Charon binary, the capture of Triton, the tilting of Uranus, or the tilting of Neptune could have occurred by itself, though each had only a small chance. But the combined probability that seven objects could cause four events would be less than one in a million billion (one in 10^{15}) over the age of the solar system (the seven objects being Uranus, Neptune, Pluto, Triton, Charon, and the two rogue objects to tilt Uranus and Neptune, and the four events being the creation of the Pluto-Charon binary, Triton's capture, and the

Icy Subdwarfs already discovered?

The search for ice dwarfs in the comet cloud is just beginning, but there is other evidence for this class of objects. Astronomers have already detected three small, icy bodies in the region between Saturn and Uranus. These icy "subdwarfs" are 2060 Chiron, Phoebe, and the newly discovered asteroid minor planet 5145 (1992 AD).

Astronomers usually classify Chiron, which was discovered in 1977, as the largest known comet. Chiron (not to be confused with Pluto's moon Charon) orbits the Sun in an unstable, 51-year-long orbit that ranges as close to the Sun as 8.5 AU and as far away as 19 AU. Estimates of its diameter range from 150 to 400 kilometers, making it about the size of the satellites Enceladus, Mimas, and Miranda. Chiron is 1,000 to 100,000 times as massive as a typical comet. In 1989, Chiron suddenly brightened and formed a coma, indicating its crust contains easily evaporated, or volatile, ices.

Computer modeling done by several groups indicates that Chiron most likely has not been in its present orbit for more than a few million years, which is a short time compared with the age of the solar system. Further calculations show that Chiron could not have stayed for a long time in an orbit close to the Sun

Phoebe

(tiltings of Uranus and Neptune). This is similar to the probability of your reaching into a hundred thousand tons of beach sand and, on the first try, pulling out the one hidden grain that was painted purple. With the various clues seen together, one finds a compelling case that each of the three outer planets gives independent evidence of events best explained by a population of several hundred to several thousand ice dwarfs.

Where the Dwarfs Are

One of the most interesting aspects of the ice dwarf theory is that the evidence for their formation is contained in a set of clues that have been known for years, but which were not previously recognized as interrelated. However, in accepting the ice dwarf hypothesis as a unifying solution to the low probabilities of the various observed characteristics of the Uranus, Neptune, and Pluto-Charon systems described above, it's natural to ask where all the ice dwarfs have gone.

The accretion epoch of giant planet formation ends when the growing planets either accrete all of the available material or gravitationally eject it from the formation region. Computer simulations of this process predict the ejection of comets from the Uranus-to-Neptune zone to the Oort cloud, which lies between a few thousand and fifty thousand AU from the Sun. Victor Safronov of the Sternberg Institute in Moscow and Julio Fernandez and Wing Ip (teaming together from their institutions in South America and Europe) have performed the most notable of these simulations.

Although the exact details of their results differ, both groups find that much more mass was ejected from the Uranus-to-Neptune zone than was incorporated into Uranus and Neptune themselves. This is because ejecting a body is dynamically more likely than capturing it. Furthermore, both groups found that much of this material was ejected from the solar system altogether. Only one-third of it or less was actually deposited in distant orbits in the Oort cloud.

Similar calculations also show that Pluto-sized planets are almost as easily ejected by Uranus and Neptune as comets are. This is because the ice dwarfs are 10,000 times lighter than Uranus and Neptune and therefore are relatively massless. This indicates that the ice dwarfs were nearly as easily removed from the Uranus-to-Neptune zone as the comets were, and that between 1 and 20 percent of the original population (several dozen to a thousand ice dwarfs) now reside in the Oort cloud.

Sleuthing the Herd

Since Clyde Tombaugh's discovery of Pluto in 1930, astronomers have searched repeatedly for a possible tenth planet. If the ice dwarf hypothesis is correct, not just one but perhaps tens or hundreds of planets remain to be discovered. However, because they are so small and distant, the ice dwarfs are beyond the 18th- to 23rd-magnitude limit of photographic surveys made to date. Typical visual magnitudes for an ice dwarf in the Oort cloud lie in the range of 31 to 37, depending upon the ice dwarf's size and distance.

Given such an observational challenge, how might astronomers

or else it would have lost all of its ices. Hence astronomers believe Chiron is a recent and unusually large intruder from the Oort comet cloud.

Phoebe, a 160-km-wide satellite of Saturn, orbits on a retrograde path that indicates that it was captured from a heliocentric orbit. Whether this capture took place recently or soon after Saturn formed, roundish Phoebe may have formed directly in the solar nebula during the epoch of giant planet formation.

Like Chiron, the recently discovered minor planet 5145 is enormous compared with comets and asteroids of average size. Estimates give its diameter as 100 to 300 km. Its orbit is also unstable, taking 93 years to orbit the Sun, reaching in to 9 AU and straying out to 30 AU.

Apparently, at least three icy subdwarfs roam the outer solar system. Two of these bodies appear to have come from the outer reaches of the solar system because they lie in short-lived, unstable orbits. The presence of these icy subdwarfs in the outer solar system adds tantalizing evidence to the claim that many small planets orbit stealthily in the Oort cloud.

NEPTUNE CAPTURED TRITON early in the history of the solar system. But the capture almost certainly would not have occurred unless hundreds of Triton-like bodies roamed the outer solar system.

find these faint objects? Calculations show that a large infrared space observatory (such as SIRTF, the proposed Space Infrared Telescope Facility) could detect the faint thermal emission of ice dwarfs located as far away as 1,000 AU from the Sun. The European Infrared Space Observatory (ISO), planned for launch in 1993, could detect ice dwarfs inside 200 AU if a dedicated search were undertaken. Preliminary calculations show that up to 10 ice dwarfs might still orbit in this region. By comparison, searches for ice dwarfs by reflected light can reach out only 150 to 200 AU; they cannot hope to probe the Oort Cloud. And the chance that the motion of a still-working outbound Voyager or Pioneer spacecraft would be perturbed by an ice dwarf's gravity is negligible.

Even with a sensitive far-infrared observatory, locating remnant ice dwarfs will not be easy. Presumably, only a small fraction of the total population of ice dwarfs orbits inside 1,000 AU. These few bodies most likely are spread rather uniformly over the sky, making their detection difficult. But if we can locate several of these icy planets, we'll have confirming evidence that the solar system formed not only the nine planets of classical and telescopic discovery but also a great number of tiny worlds too.

Perhaps Not Nine, But Nine Hundred

Although astronomers have not yet detected any of these now-distant icy planets, there seem to be several lines of evidence indicating the presence of numerous ice dwarfs in the past. This strong but circumstantial evidence reminds us of archaeological studies that conclude early humans used fire at a given site, basing the conclusion on the presence of scattered flint tools and cooking utensils — even though there were no burnt logs themselves.

Still, direct detection of distant ice dwarfs will be required to seal the case. If distant ice dwarfs are discovered and their origin in the Uranus-to-Neptune zone is confirmed by detailed computer modeling, then our perspective on the outer solar system will undergo some significant changes:

First, Pluto will no longer be considered an oddity outside the paradigm of planetary formation. Indeed it, like Charon and Triton, would be viewed as one of the few remaining precious relics of the once-prevalent ice dwarf population. They will be immensely valuable for scientific study.

Second, we will see that the era of runaway planetesimal growth that led to the formation of Uranus and Neptune took place after (or lasted long enough to allow for) the formation of a significant number of giant planet embryos the size of planets and not just comets.

And last, our census of the solar system's planetary population will be dominated by a class of small, icy worlds not even recognized to exist until the great wave of spacecraft reconnaissance in the late 20th century was already complete. ☐

Alan Stern is a planetary scientist at Southwest Research Institute in San Antonio, Texas.